

techniques that should lead to a sharper less-distorted focus. This should reduce the throughput loss and bring it closer to the theoretical limit.

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## GaAs-GaAlAs injection lasers on semi-insulating substrates using laterally diffused junctions<sup>a)</sup>

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Low-threshold GaAs-GaAlAs lasers operating in a stable single mode have been fabricated using laterally diffused junctions. The lasers are fabricated on semi-insulating substrates and can be integrated with other components.

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We have recently reported on the fabrication, for the first time, of GaAs-GaAlAs injection lasers on semi-insulating substrates.<sup>1</sup> Such lasers will be necessary for integration into complex monolithic optical circuits where individual active components need be electrically insulated from each other.<sup>2</sup> In the reported laser the gain region was limited transversely to a narrow stripe by the current crowding effect. It oscillated in a number of transverse modes, making for unstable spatial and spectral characteristics. These instabilities were largely eliminated by resorting to lateral injection of current from a zinc-diffused  $p^+$  region. The resulting lasers, in addition to their stability, have very low threshold currents.

The laser consists of a three-epilayer double heterostructure on a semi-insulating substrate and a Zn-diffused region, as shown in Fig. 1(b). The current entering through the  $p$ -type contact flows laterally across the junction to the  $n$  side. Since GaAlAs has a wider band gap than that of GaAs, carriers are injected predominantly across the GaAs  $p$ - $n$  junction. Unlike the conventional stripe-geometry lasers, the effective area of current injection in this structure is determined by the thickness of the GaAs layer. Low-threshold lasers can be achieved, as submicron GaAs active layers can easily be grown using liquid-phase epitaxy. This method of transverse injection was first used by Namizaki *et al.* to make transverse junction stripe (TJS) lasers on  $n^+$  GaAs substrates.<sup>3</sup> However, their structure suffered from current leakage across the (diffused)  $p$  GaAlAs- $n$  GaAlAs junction which made for a rapid increase of the threshold current at higher temperatures.<sup>4</sup> Susaki *et al.* recently used  $p$ -type substrates and a  $pnpn$  structure in the undiffused region to eliminate this problem.<sup>5</sup> In our structure, which needs only

three epilayers, this current leakage is eliminated because the substrate is semi-insulating GaAs.

When fabricating the lasers we first grew in sequence the three  $n$ -type layers  $\text{Ga}_{1-x}\text{Al}_x\text{As}$ , GaAs,  $\text{Ga}_{1-x}\text{Al}_x\text{As}$  ( $x \sim 0.45$ ) and then an undoped GaAs layer. The first three layers form a double heterostructure in the vertical direction. The top GaAs layer was used as a diffusion mask. The reason for using GaAs as the diffusion mask is our finding that the Zn diffusion coefficient in GaAs is much smaller than that in GaAlAs, and that the higher the Al concentration (at least up to  $x = 0.45$ ), the faster the diffusion. By using a normal epitaxially grown GaAs layer as a mask, we eliminate the extra step of depositing a mask. In addition, the GaAs layer is more stable than the regular masking layer, since no stress exists between the mask and the layer under it. The Zn diffusion was performed in two steps after etching away a part of the top GaAs layer. The diffusion source was  $\text{ZnAs}_2$ . The first diffusion took place at  $660^\circ\text{C}$  for 1 h. The cross section of the layers after the first diffusion is shown in Fig. 1(a). Owing to the

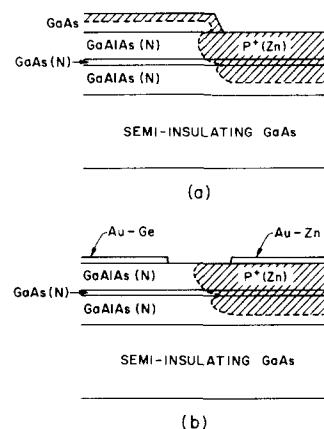


FIG. 1. (a) The cross section of the laser after the first-step diffusion. Right-hand side of the top GaAs layer is etched away. The remaining part serves as a diffusion mask. (b) The cross section of the final structure.

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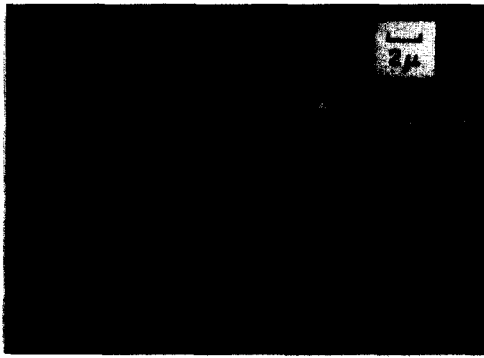


FIG. 2. A SEM picture of the cross section of a laser. The right-hand side is the Zn-diffused region. Two boundaries correspond to two-step diffusion. The shape of the diffusion front shows different diffusion rates in GaAs and GaAlAs.

different diffusion rates of Zn in GaAs and GaAlAs, the diffusion depth is much larger in the unmasked region. We then etched away the remaining GaAs mask selectively.<sup>6</sup> Heat treatment was subsequently performed at 860°C for 1.5 h. Following that, metal contacts of Au-Zn on the *p* side and Au-Ge on the *n* side were applied separately. The laser chip was mounted on a Cu heat sink with the two contact leads pointing up. The final structure of the laser is shown schematically in Fig. 1(b). Figure 2 is a SEM picture of the cross section. Two diffusion fronts can be seen which are due to the two-step diffusion. The shape of the diffusion front shows very clearly that the diffusion in GaAs is slower than that in GaAlAs. In the GaAs region the diffusion front is not perpendicular but tilted at an angle to the plane of the epilayers. The width of the *p*-*n* junction in this region is wider than the thickness of the GaAs layer. Because of this, the laser is not the pure homostructure laser described in Refs. 4 and 5, but a combination of the homostructure and the heterostructure.

We have studied the properties of lasers with different doping concentration in the GaAs layer. We found that this concentration strongly affects the lasing characteristics. Figure 3 shows the near field and the far field of a laser when the doping concentration is low ( $\sim 10^{17} \text{ cm}^{-3}$ , Sn doped). The near field has a small tail penetrating into the *n* side. As the current increases ( $> 1.5I_{th}$ ) more modes appear on the *n* side. The far

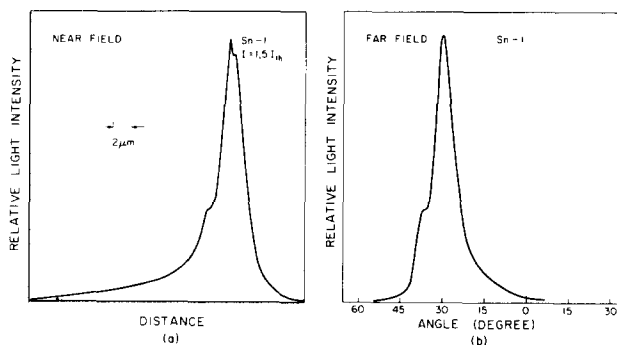


FIG. 3. (a) The near field and (b) the far field of a laser with a lightly doped GaAs layer ( $\sim 1 \times 10^{17} \text{ cm}^{-3}$ , Sn doped). The left-hand side of each picture is the *n* side, while the right-hand side is the *p* side.

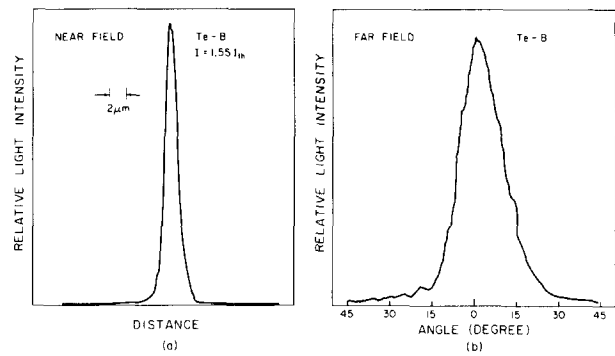


FIG. 4 (a) The near field and (b) the far field of a laser with a heavily doped GaAs layer ( $\sim 7 \times 10^{18} \text{ cm}^{-3}$ , Te doped). The left hand side of each picture is the *N* side, while the right side is the *P* side.

field shows that the light is emitted at an angle with respect to the normal direction to the *n* side. The maximum intensity appears at about  $30^\circ$ . This can be explained as follows: When the doping concentration of the *n* side of the junction is much lower than that of the *p* side, most of the recombination is due to hole injection. The laser light generated in the active region is guided along the junction by the mechanism of gain-loss guiding. The gain-loss profile in the *n* side decays as we go further away from the junction. This results in the normal to the wave fronts of the laser mode being pointed toward the *n* side. Consequently, as the laser light exists from the mirror surface, it propagates toward the *n* side. This phenomenon has also been observed in some other laser structure.<sup>7,8</sup> When the *n*-type doping concentration of the GaAs layer is increased, the near field becomes narrower and the peak of the far field moves toward the center. Figures 4(a) and 4(b), for example, show the near field and the far field of lasers with a highly doped GaAs layer ( $\sim 7 \times 10^{18} \text{ cm}^{-3}$ , Te doped). The near field is very narrow with a

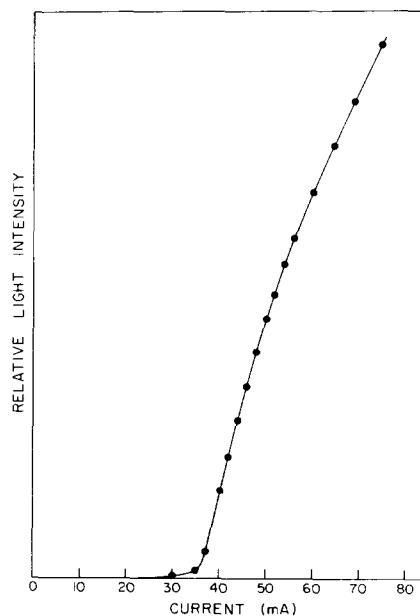


FIG. 5. The light-vs-current curve of a laser with a threshold of 36 mA.

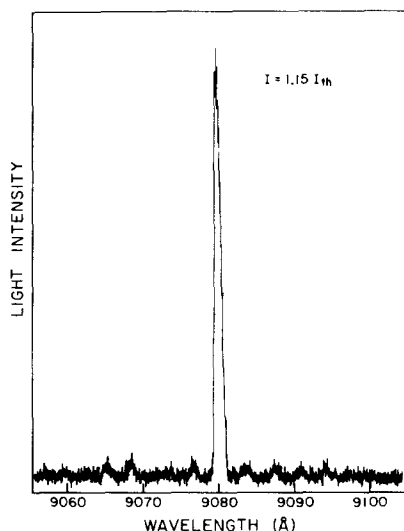


FIG. 6. The spectrum of a laser displaying a single longitudinal mode.

half-width of less than  $2\ \mu\text{m}$ . It corresponds to a single mode and stays stable as the current increases. The tail which appears on the  $n$  side at low doping concentrations is absent. These changes can be explained qualitatively as being caused by the fact that at some sufficiently high  $n$  doping, the increased electron injection to the  $p$  side causes the gain-loss profile to become symmetric about the junction plane. The far field, which is symmetric and centered at  $0^\circ$ , resembles the usual far field of the conventional stripe-geometry lasers.

The  $n$ -type dopant we used for the GaAs layer is Sn for low doping and Te for high doping. The lasers with the lowest threshold currents have doping concentration of about  $4 \times 10^{18}\ \text{cm}^{-3}$  (Sn doped). The lasing threshold of a  $300\text{-}\mu\text{m}$ -long diode under pulsed operation is about 40 mA. Figure 5 shows the measured light intensity curve as a function of driving current. The threshold is 36 mA. The curve shows no kinks as the current is increased up to two times the threshold value. The near

field and the far field are similar to that shown in Fig. 4.

The spectrum of the emitted light also varies as the  $n$ -type doping concentration in the GaAs layer is changed. At the low concentrations the spectrum shows the existence of a number of longitudinal modes. When the concentration is higher than about  $5 \times 10^{18}\ \text{cm}^{-3}$  (obtained by Te doping) a single longitudinal mode is observed. Figure 6 is the spectrum of one of these lasers. The oscillation wavelength is longer than that of the lasers with lower doping concentration, which might be due to the band tailing at high concentration.

In conclusion, we have combined the Zn diffusion with heteroepitaxy to fabricate lasers on semi-insulating substrates. GaAs was found to be a good mask for Zn diffusion. The dependence of the mode structure and the spectrum on the doping concentration of the GaAs layer have been studied. Thresholds as low as 35 mA have been achieved.

Because the lasers are fabricated on semi-insulating GaAs substrates, it is possible that integration with other devices such as GaAs Schottky FET and Gunn device<sup>9</sup> can be achieved.

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